The MECO Scientific Collaboration

Collaboration of eleven institutions at present, one very recent addition (Dubna) not listed here, talks ongoing with others

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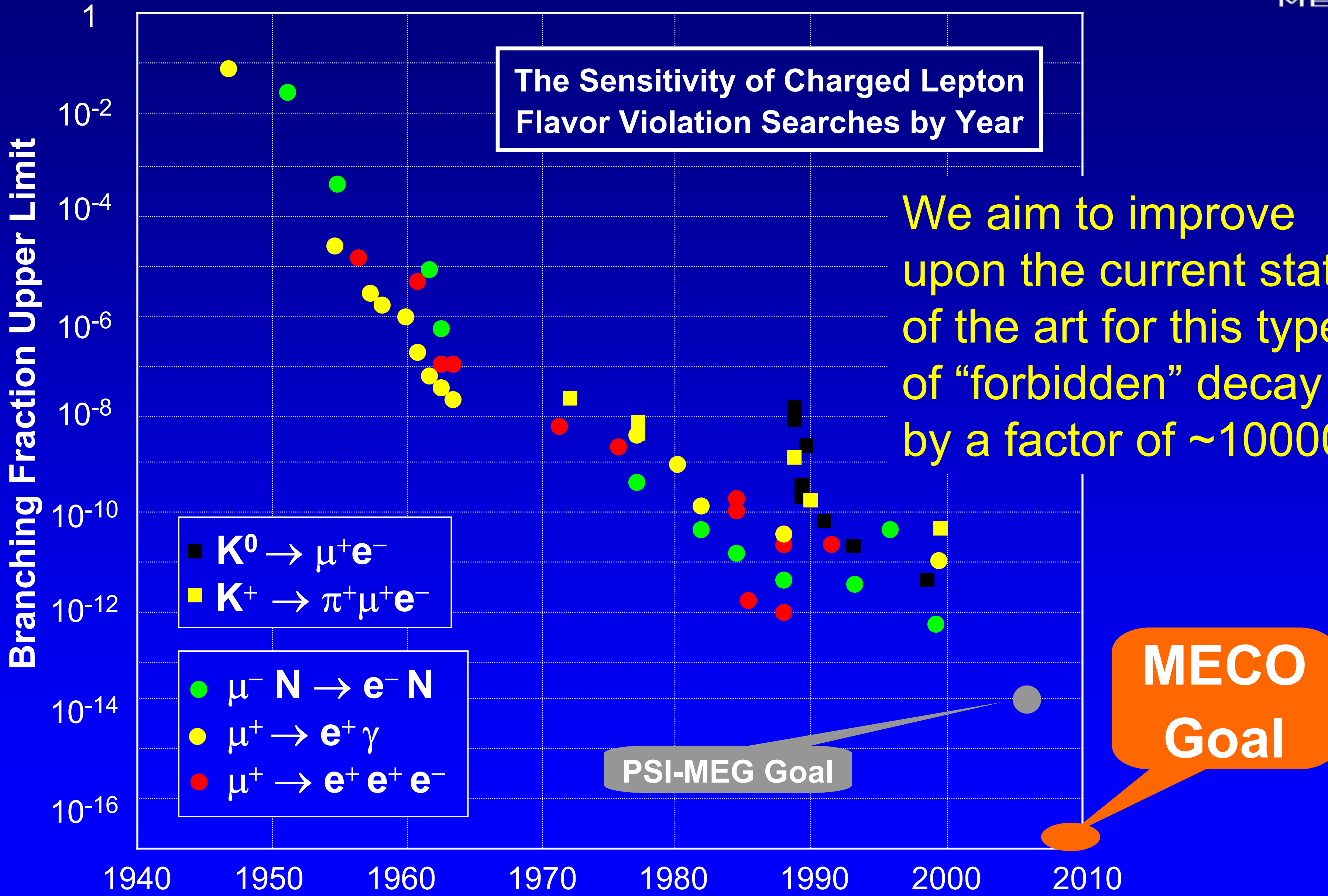
Four Orders of Magnitude



We aim to improve upon the current state of the art for this type of “forbidden” decay by a factor of ~10000

Muon to Electron Conversion

- Low energy muons are stopped in thin Al foils, forming muonic atoms

- Three possible fates for the muon
  - Nuclear capture $\quad \mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1)$
  - Three body decay in orbit $\quad \mu^- \rightarrow e^- \, \nu_\mu \, \bar{\nu}_e$
  - Coherent Lepton Flavor Violating decay $\quad \mu^- + (A,Z) \rightarrow e^- + (A,Z)$

- Signal is a single mono-energetic electron originating the stopping target

$$E_e = m_\mu - E_{recoil} - E_{binding} \approx 105\ \text{MeV}$$

- Achieving the desired sensitivity will require ~10^{18} stopped muons and extremely tight control of possible background sources

MECO's Required Intensity

The MECO intensity requirement is driven by the need to reach the desired sensitivity of 2×10^{-17} to muon conversion in a reasonable length of time.

The latter is assumed to be 35 weeks of running 80 hours /week or approximately 10^{7} s of beam on target.

This yields 40 Tp / sec and a total of 4×10^{20} protons delivered.

Uncertainty in muon yield could require as much as 50% more running time to reach design sensitivity.

If background limit is not reached at that point, additional running = greater sensitivity.

Contributions	Factor
Required Muon Sample	5×10^{16}
Running time (s)	$\div10^{7}$
μ reaching stopping target per incident proton	$\div$ 0.0043
μ stopping probability	$\div$ 0.58
μ capture probability	$\div$ 0.60
Fraction of μ capture within detection time window	$\div$ 0.49
Electron trigger efficiency	$\div$ 0.90
Fitting and selection criteria efficiency	$\div$ 0.19
Required Proton flux (Hz)	$= 4\times10^{13}$

MECO's Beam Momentum

The MECO beam momentum is chosen to be 7.5 GeV/c as a compromise between two competing effects

- The production of anti-protons, a source of late background, increases rapidly above threshold (~6 GeV, depends upon target Fermi momentum)
- The pion production rate, and thus the number of stopped muons per incident proton, increases with beam momentum

This choice also has the advantage of being below transition in the AGS

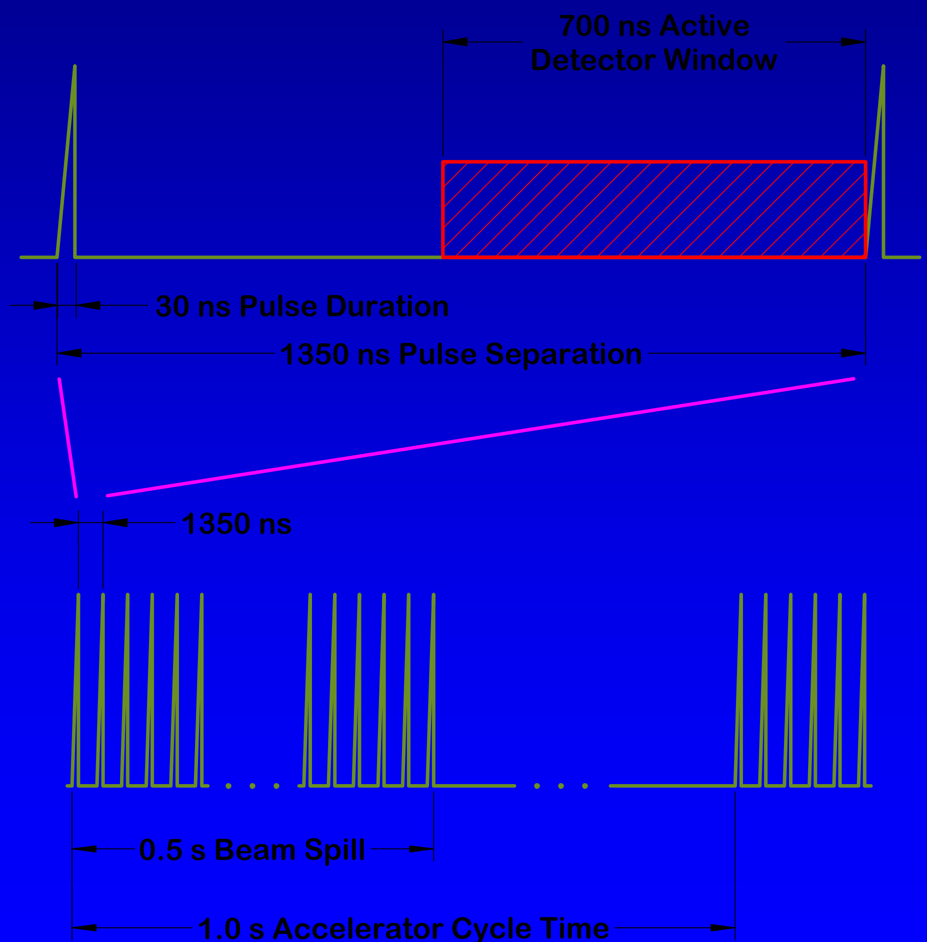
The problem with anti-protons

- Only low momentum $\bar{p}$ will traverse the Transport Solenoid
- These have very low kinetic energy, i.e. very long transit time, making them a source of prompt background during the measurement interval unless they are suppressed

MECO's Pulsed Beam

The $\mu^- N \to e^- N$ signal persists much longer than many potential background sources due to the ~1 μs muon lifetime when bound to an Al nucleus

We suppress prompt backgrounds by accepting conversion e^- candidates that arrive *well* after the proton beam strikes the target.



This necessitates pulsing the proton beam:

– Beam pulse duration << μ lifetime

– Pulse separation $\cong$ μ lifetime

– Extinction (the fraction of beam arriving between pulses) < 10^{-9}

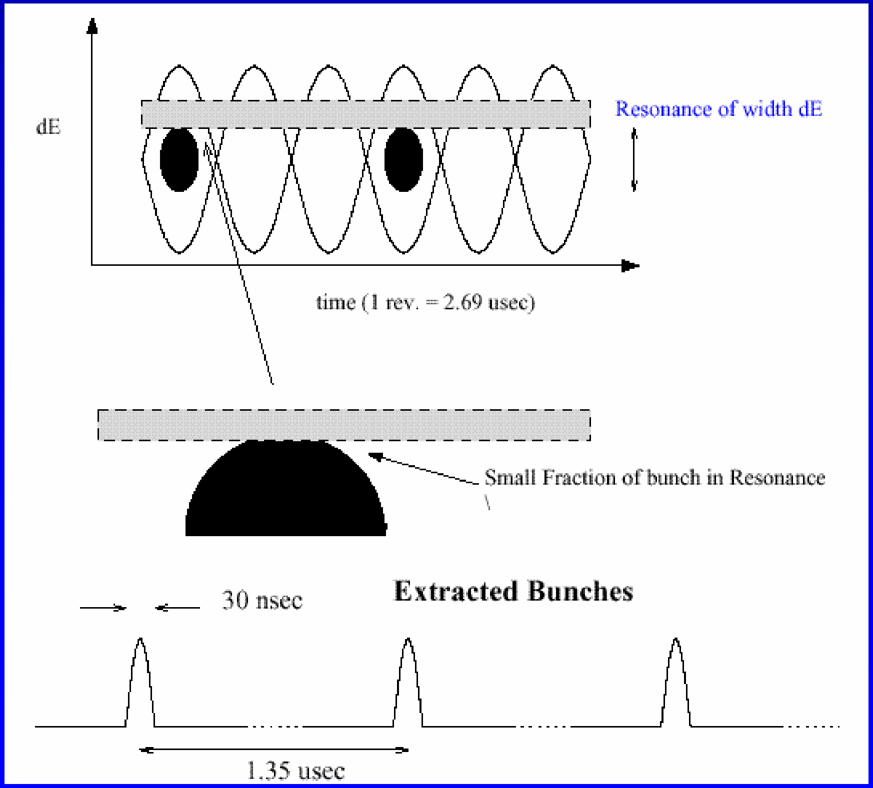
Bunched Extraction

Slow resonant extraction with RF on provides the desired structure with two filled buckets out of the nominal six

- RF accelerates the beam into extraction resonance
- A small slice of phase space is peeled off from the bunch

This scheme establishes the required time structure, but the unfilled buckets are a potential source of out-of-time protons

When combined with the intensity requirement, this implies 20 Tp per bunch, which is ~8 Tp more than previously demonstrated in the AGS



Bunch Intensity Limits

The present per-bunch intensity limit comprises

– Space charge effects during accumulation, 800 ms nominally

  $\Rightarrow$ 133 ms (one Booster cycle) for MECO

– Momentum aperture constriction at transition prevents use of full longitudinal acceptance of AGS

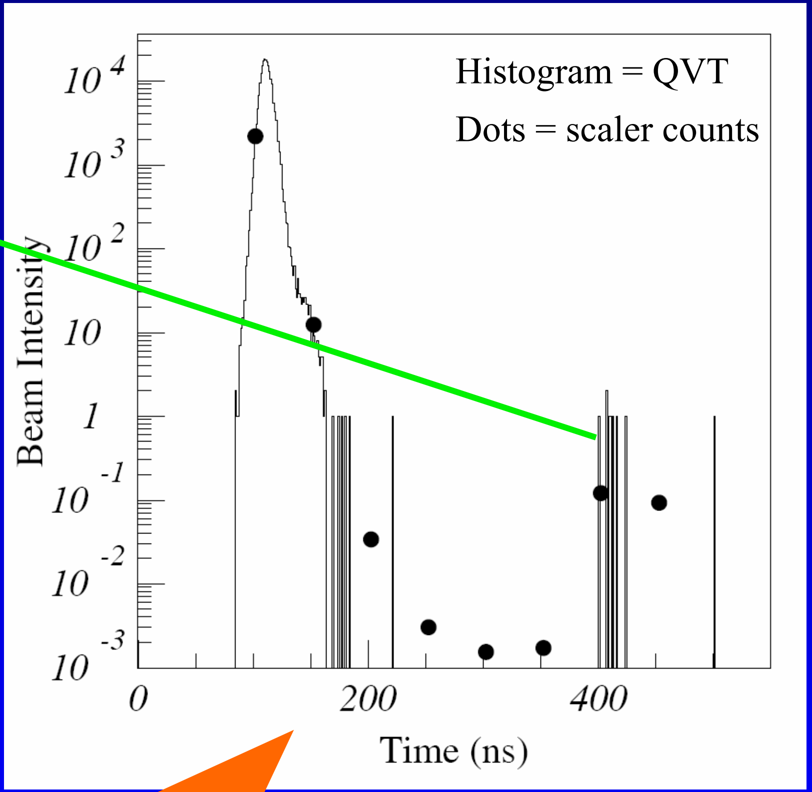
  $\Rightarrow$ MECO running below transition removes this constraint

Machine studies are required to determine whether the above factors are sufficient to achieve 20 Tp / bunch

We may face overall intensity limits due to ALARA concerns operating at 40 Tp/s.

Early Extinction Measurements

- Initial test at 24 GeV/c with one bucket in the AGS yielded $<10^{-6}$ extinction between buckets and 10^{-3} in unfilled buckets
- A second test at 7.4 GeV/c with a single bucket found $<10^{-7}$ extinction
- Test time was insufficient in either case to optimize the extinction during the test
- It is possible that careful tuning alone will suffice to achieve $<10^{-9}$ but we are conservatively assuming that it will not



Beam Intensity vs. Time modulo 1.35 μs during test with E871 trigger

Extinction Enhancement

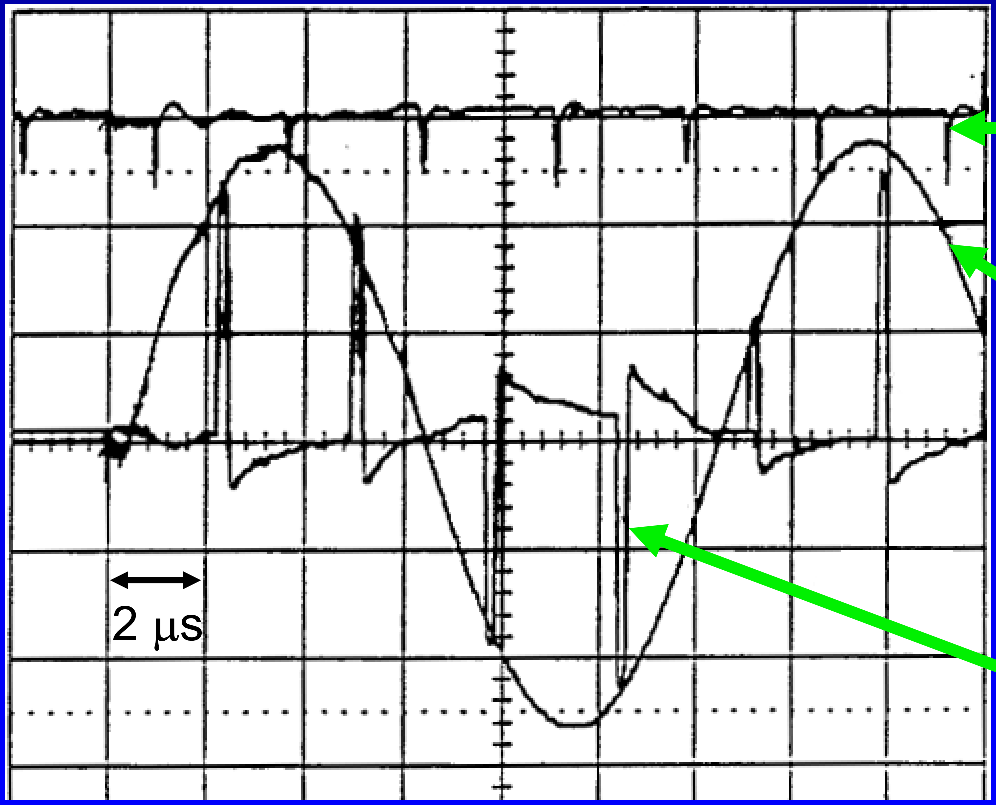
We are taking a "belt and suspenders" approach to extinction enhancement given the critical need to control backgrounds in the experiment

- AGS Internal Hardware
  - An AC Dipole Magnet to drive beam out of the machine
  - A Kicker system to offset the AC dipole signal during the passage of filled beam buckets
- External hardware in the extraction line
  - An RF modulated dipole to provide maximal kick only to protons within the nominally filled buckets
  - Lambertson magnets to separate beam protons from out-of-time protons receiving smaller kick in the RF dipole
  - A small cross-section target, limiting allowed beam trajectories

AGS Internal Extinction

- Stripline AC dipole at 80 kHz excites coherent vertical betatron resonance
- Fast (100 ns) kickers cancel AC dipole at the bunches
- Kicker duty factor is low 100 ns / 2.7μs = 4%

- Concept tested in FY98 using existing AC dipole and kickers

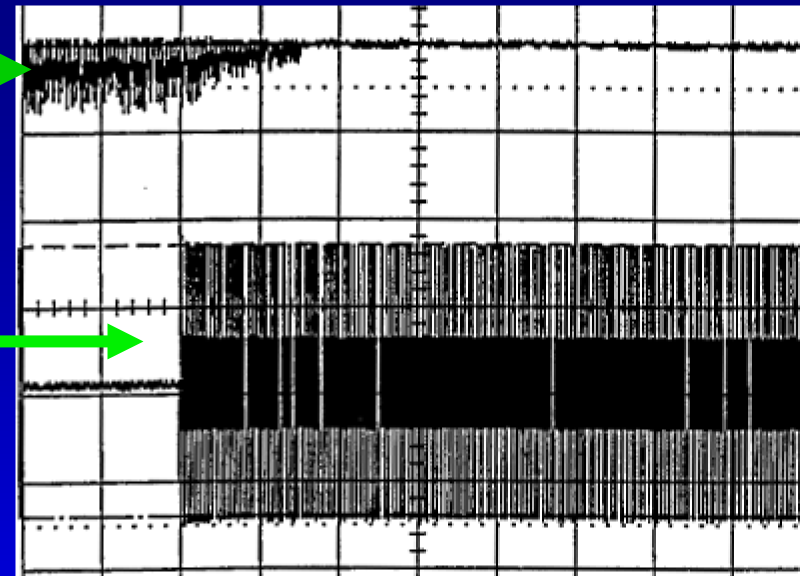


FY98 AGS Extinction Tests

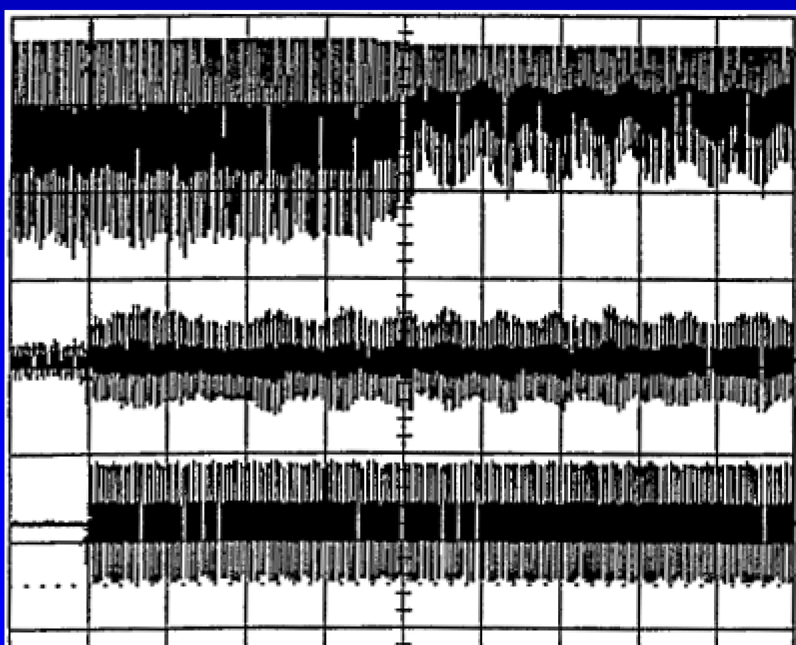
Beam Intensity

AC Dipole drives beam out of the machine in 20 ms

AC Dipole On



10 ms



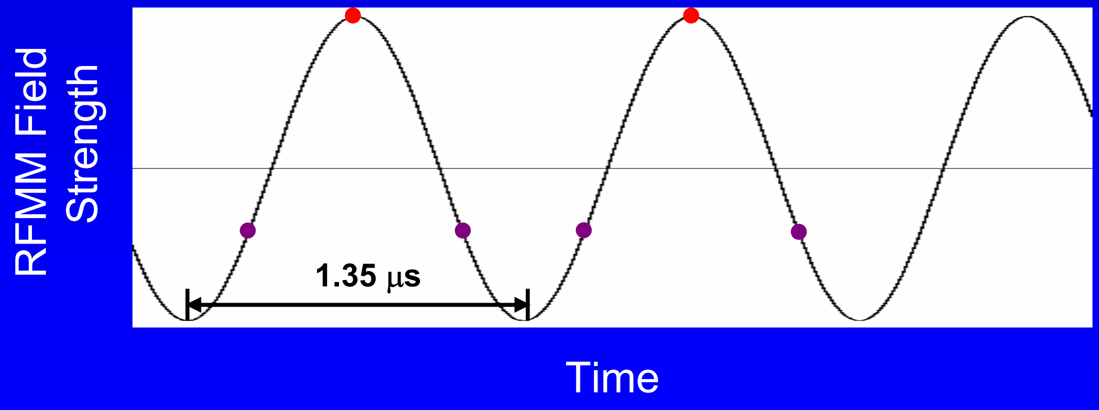
Kicker

AC Dipole (reduced voltage)

Kicker restores beam (note that it is too weak to do so completely)

Extinction in the Extraction Line

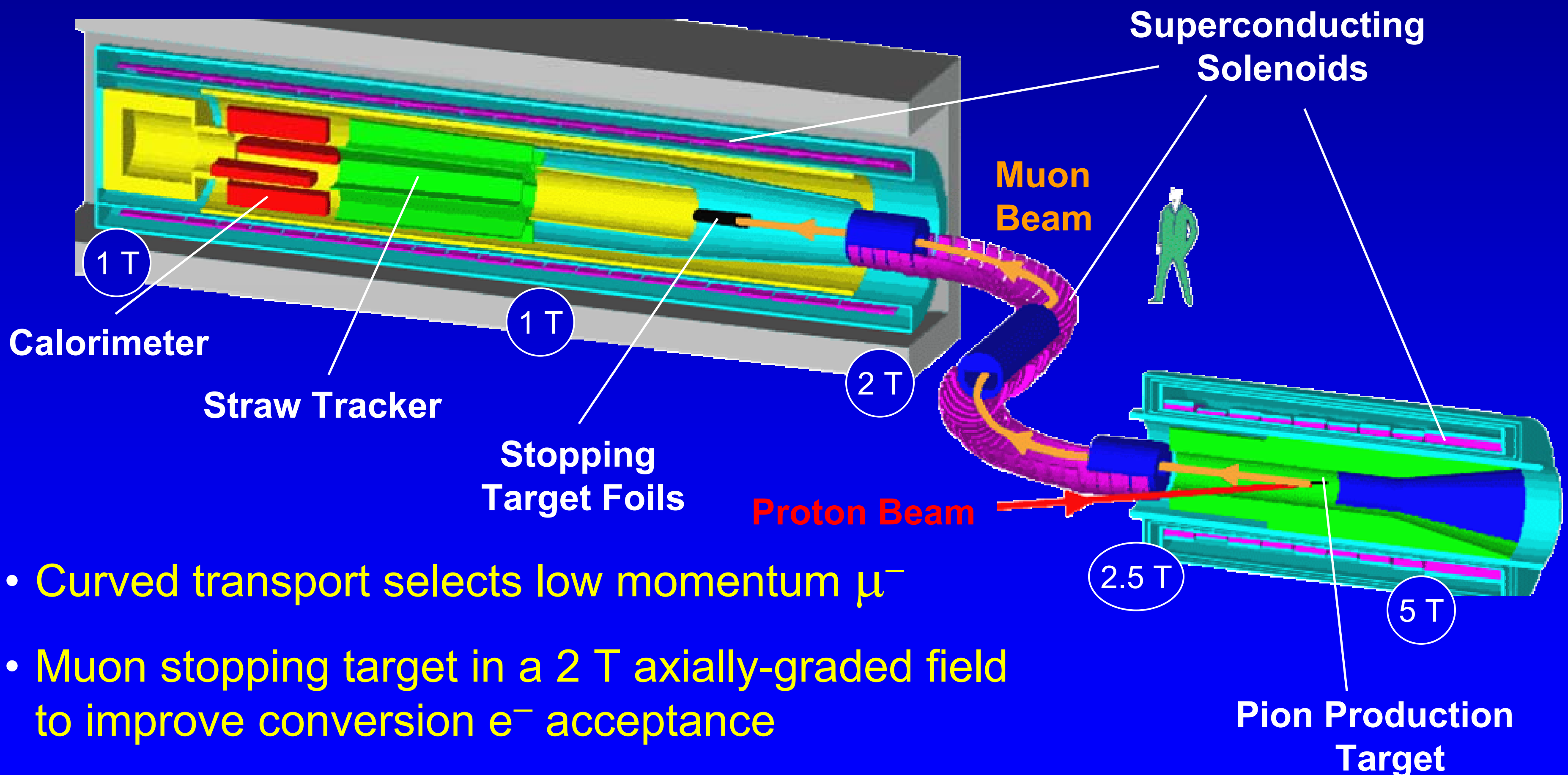
- RF Modulated Dipole + Lambertson Magnets + Small Production Target
  - Filled buckets
    - Arrival at RF dipole coincides with maximum field in the dipole
    - Beam is deflected into shielded channels in Lambertsons
  - Beam arriving out-of-time (empty buckets)
    - Receives less than maximal deflection in dipole
    - Enters diversion channels in Lambertsons
- Counters placed downstream of the Lambertsons serve as a monitor



- Nominally filled buckets receive the maximum kick
- Unfilled buckets receive negative kick

Features of MECO

- 1000–fold increase in μ beam intensity over existing facilities
  - High Z target for improved pion production
  - Axially-graded 5 T solenoidal field to maximize pion capture



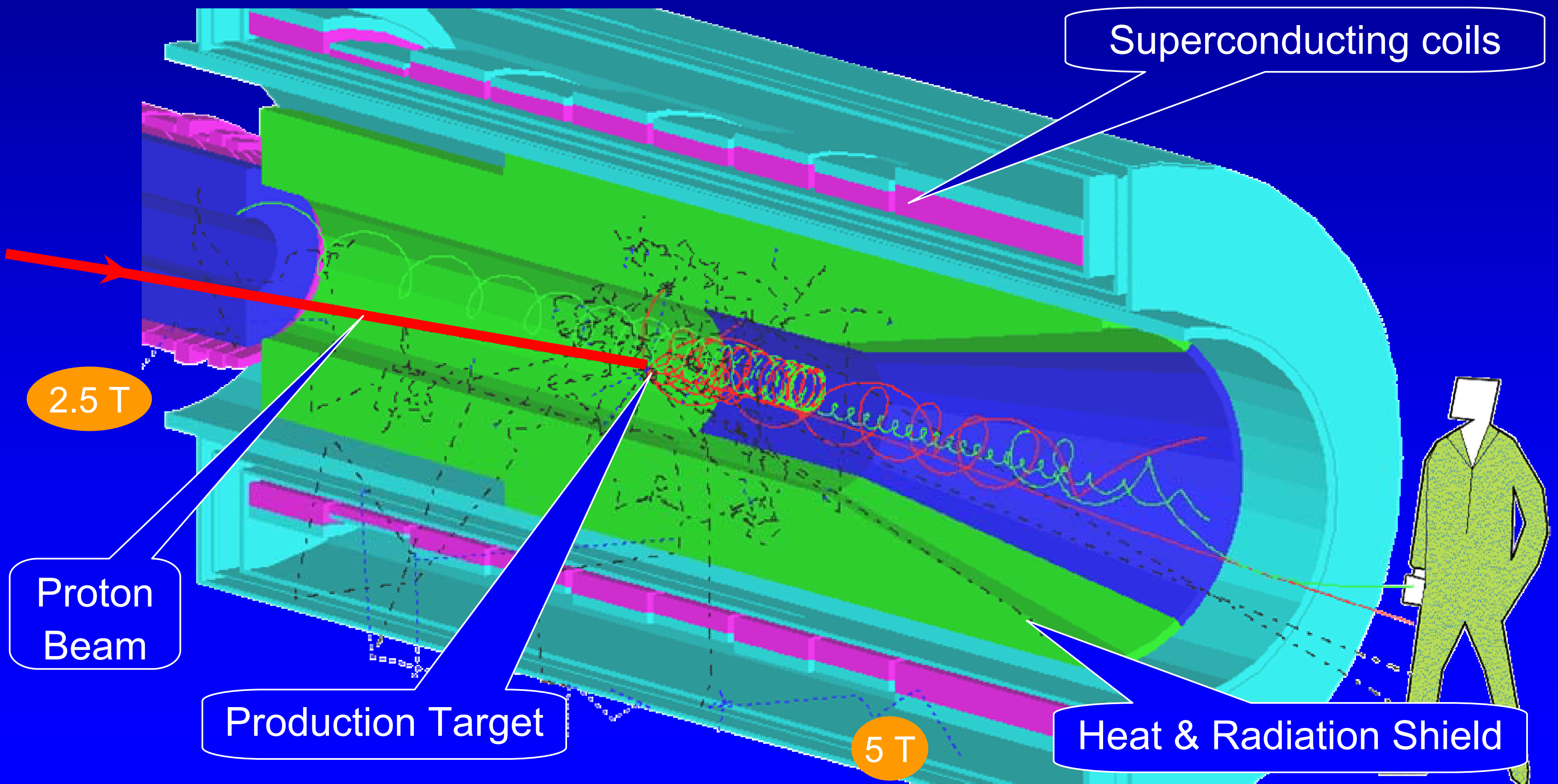
- Curved transport selects low momentum μ^-
- Muon stopping target in a 2 T axially-graded field to improve conversion e^- acceptance
- High rate capability e^- detectors in a constant 1 T field

Targeting Requirements

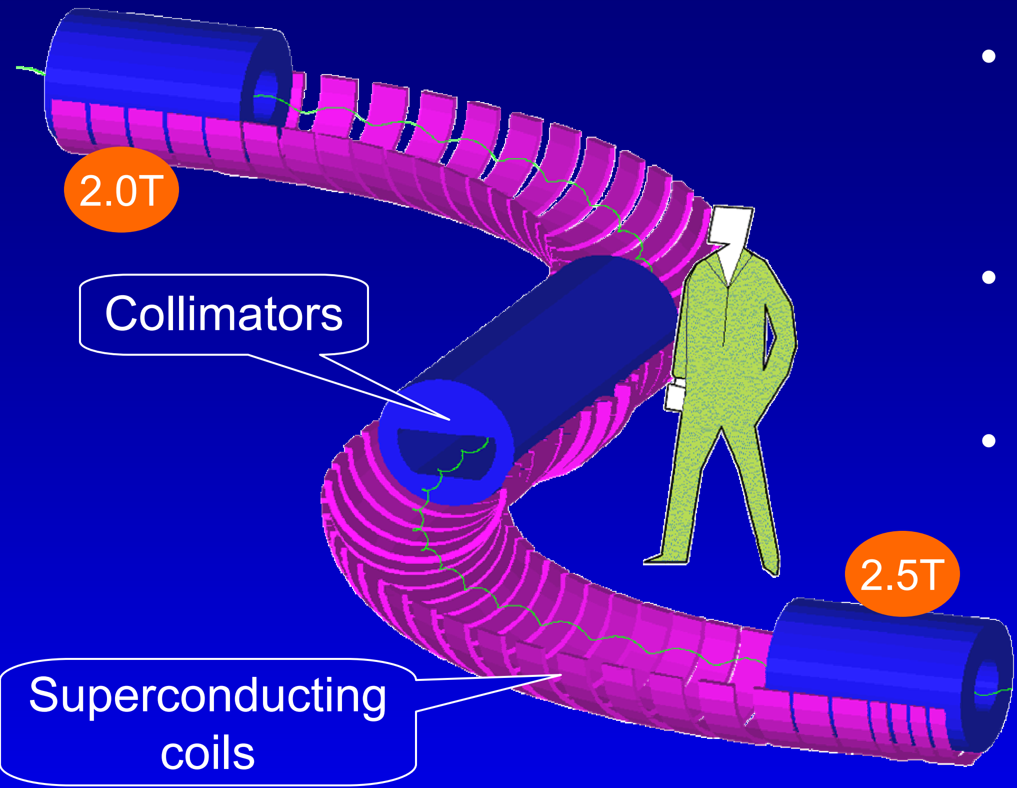
- Muon Yield: The target must be compact and have minimal material around it to avoid reabsorbing pions from the primary interaction before they produce muons.
- Extinction: The dimension of the target transverse to the beam should be small to minimize the phase space for protons intercepting the target after receiving less than the maximal kick in the RFMM
- Beam Spot: the preceding requirements imply a small ($\sigma_{radius} \cong 1$ mm) beam spot in order to keep ~95% of the beam on the target
- Aperture Limits: The beam must pass through the complex region of the PS – TS interface. The area available for the beam is limited. Particularly as shielding is needed to protect the coils from beam fault conditions.
- Adjustability: the field in the MECO solenoids can be reversed for calibration studies, but the beam must still strike the target. The downstream beam steering magnets must accommodate the difference in incoming trajectory needed for this.

Production Region

- Axially graded 5 T solenoid captures pions and muons, transporting them toward the stopping target
- Cu and W heat and radiation shield protects superconducting coils from effects of 50kW primary proton beam

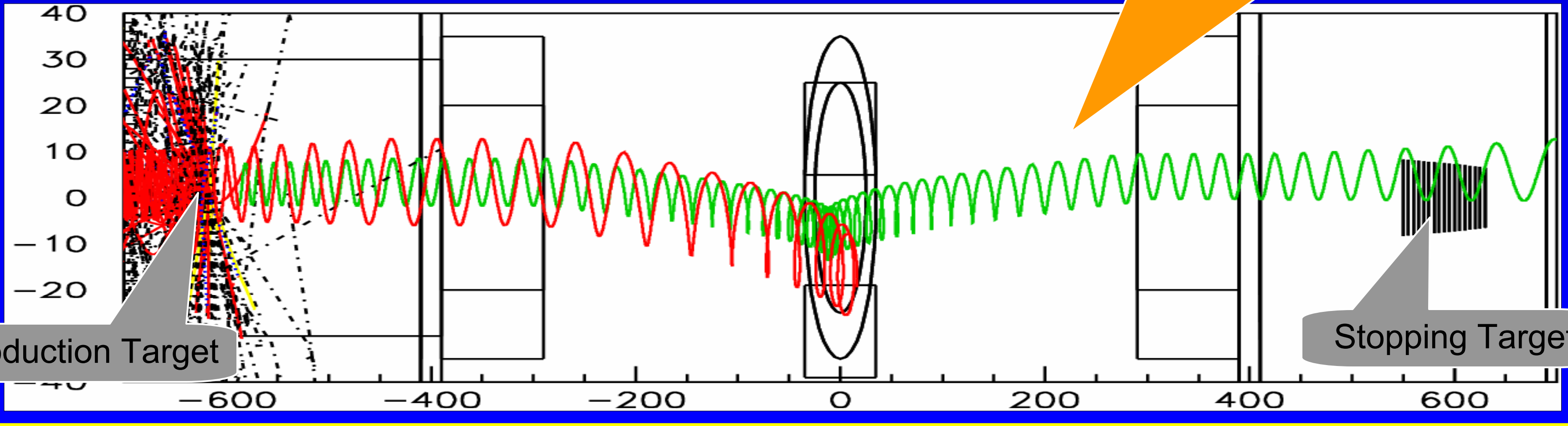


Transport Solenoid



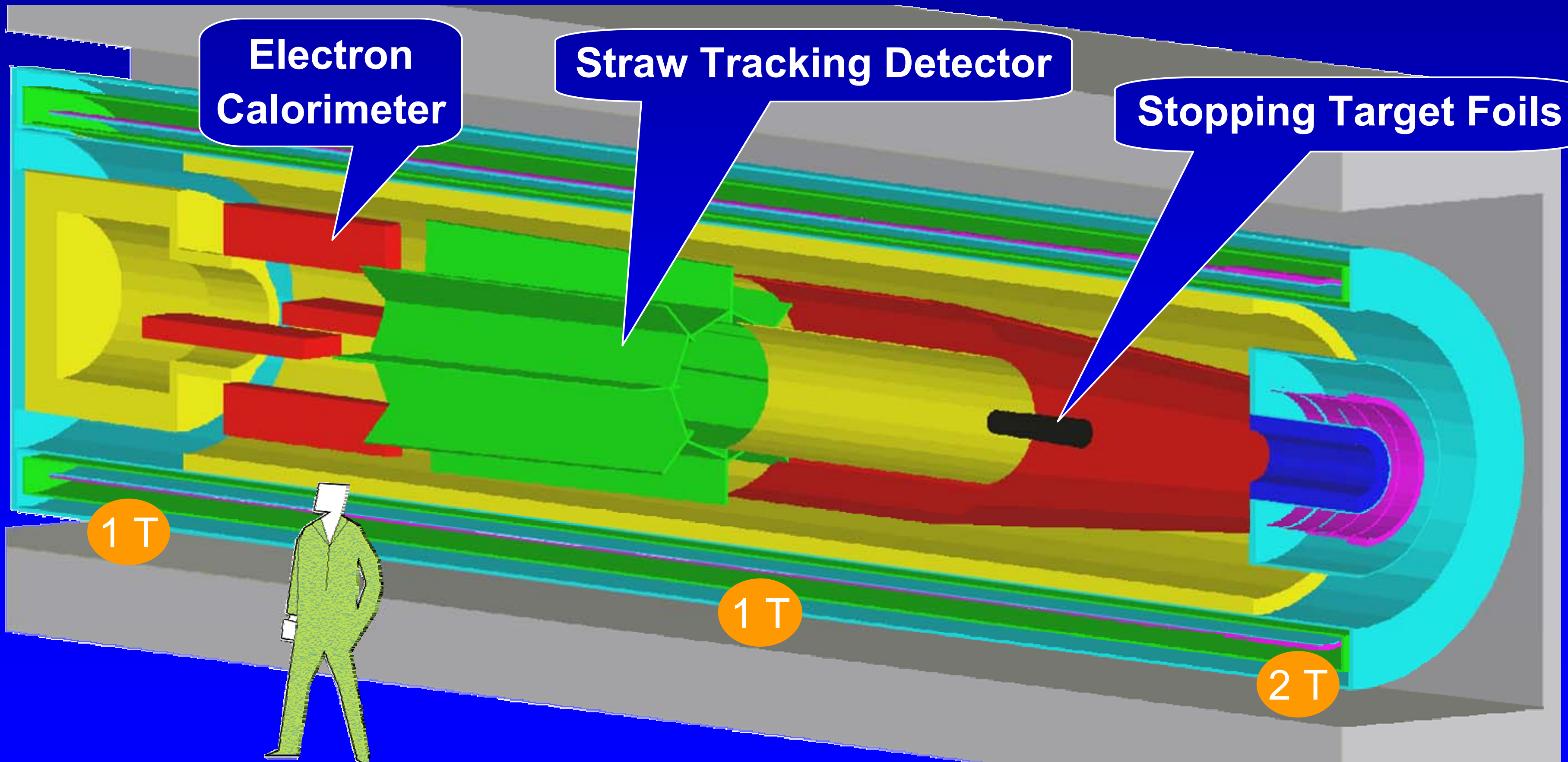
- Curved solenoid eliminates line-of-sight transport of photons and neutrons
- Curvature drift and collimators sign and momentum select muon beam
- dB/ds < 0 in the straight sections to avoid long transit time trajectories

Vertical curvature drift in TS bend sections selects low momentum μ^-



Detector Region

- Axially-graded field near stopping target to increase acceptance and reduce cosmic ray background
- Uniform field in spectrometer region to simplify momentum analysis
- Electron detectors downstream of target to reduce rates from γ and neutrons



Reiterating MECO Beam Requirements

- Beam momentum = 7.5 GeV/c
- Two bunches in the AGS at 180° (τ = 1.35 μs) with 20 Tp each
- Beam slow extracted over 0.5 s in < 50 ns wide bunches with a 1.0 s cycle time
- Inter-bunch extinction ratio, 1:10^9 or better
- Narrow focus ($\sigma_{radius} \cong$1 mm) beam on a small cross-section target with minimal material around it
- Flexibility in the steering to allow for beam on target with MECO solenoids in either polarity
- At a minimum (in the ideal case) 4 $\times 10^{20}$ protons delivered, reaching design sensitivity could require 50% more